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Hydrogen production utilizing glycerol from renewable feedstocks—The case of Brazil

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ABSTRACT

Various reports concerning catalytic reaction of glycerol for hydrogen production is available. However, economic analyses of this activity are not found yet. The objective of this work is to evaluate the process of hydrogen production via steam reforming of glycerol obtained through transesterification process of bio-oils. The thermochemical process of steam reforming process was determined due to high efficiency, feasibility and lower cost of design, development, operation and maintenance. These bio-oils come from feedstocks largely encountered in Brazil such as soybean, palm, castor bean, peanut and cotton seed as also come from residues such as defective coffee, tallow beef, wastewater (scum) and others. Various findings were obtained such as potential of production of glycerol utilizing residues (considering available amounts in the Brazilian states) and some vegetable feedstocks (considering production of harvested feedstock per hectare). Subsequently, production of hydrogen via steam reforming of generated glycerol, and foreseen electricity production via fuel cells were also determined. An additional estimation was paid for production of H-BIO, an innovative fuel developed by PETROBRAS (Petróleo Brasileiro S.A.), where hydrogen and bio-fuel are utilized and generates propane as co-product. About this work, it was concluded that high amounts of hydrogen and electricity could be produced considering an enormous potential from each cited feedstock being an attractive alternative as distributed electricity source and as an additional source for some activities, inclusively those that produce their own feedstocks such as abattoirs (beef tallow), and wastewater treatment plants.

Contents

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Nomenclature

CTC	Centro de Tecnologia Canavieira
DME	dimethyl ether
FAEE	fatty-acid ethyl ester
F.T.	Fischer–Tropsch
LPG	liquefied petroleum gas
PEMFC	proton exchange membrane fuel cell
PETROBRAS	Petróleo Brasileiro S.A.
RERs	response reactions
SOFC	solid oxide fuel cells

1. Introduction

The utilization of hydrogen will allow the energy generation with less emission in various activities such as electricity generation and automotive chain. Various other technologies could be developed in association with hydrogen chain. However the hydrogen production technologies for electricity generation purposes are not cost effective in this moment. The trend is diminishing costs of hydrogen production and hydrogen generation systems design, assembly and optimization beyond concerning with volume or weight of hydrogen systems (in the case of vehicles and portable applications). An additional infrastructure of production and distribution must also be taken into account.

Fig. 1 depicts potential of the market and technology innovation of cited technologies. Every cited technology usually utilizes renewable sources.

Various renewable sources can be utilized to generate hydrogen. In this work glycerol is cited since increasing volume to be produced is due to increasing biodiesel production spurred by program developed by Brazilian Ministry of Mines and Energy (in 2010, B5 fuel, i.e., 5% of biodiesel in the composition of commercialized diesel oil in Brazil could already be commercialized) [2]. Glycerol is a co-product of biodiesel production processes via transesterification, due to crescent production and hence, increase of its offer, its price of commercialization is diminishing. However, various steps must being followed such as purification of some glycerol to be utilized as feedstock of hydrogen in catalytic reactions. Other suggested products utilizing glycerol are 1,3-propanediol, succinic acid, 1,2-propanediol, dihydroxyacetone, polyesters, polyglycerols and polyhydroxyalkanoates [3].

In Brazil, various glycerol sources could be utilized such as vegetable and animal feedstocks. The utilization of feedstocks depends strongly on potentialities of each region. Brazil has 76,697,324 ha utilized for various cultures, especially soybean, corn (maize) and sugarcane [4]. A supplementary area of 102,170,538 ha (12% of overall Brazilian territory) is also able to cultivation [5]. Additionally, an area of 172,333,073 ha is comprised by field, which is occupied by bovines [4]. However, the density of the bovine cattle is extremely low, attaining only 1.2 bovine per hectare (considering 205,886 millions of bovines in 2006 as seen in IBGE [4]), varying according with the state [4]. This amount could be easily increased, this enormous area is also utilized for agriculture, guaranteeing a major food, feed and fuel production, revenue, and jobs. Following Scot Consultoria [6], to obtain 8 heads per hectare is possible.

Due to the increase of demand and the increase of price of petroleum-based fuels, production of biofuels (such as ethanol and biodiesel) is ever-increasing. However, an attention must also be paid concerning food and feed production since, in some cases, ethanol production from cereals such as corn (in USA), and wheat and sorghum (in Europe) have contributed to the increase of food and feed prices due to displacing of cultures for fuel production. In some cases, substitution of native vegetation for biodiesel production is unfortunately observed in countries of Southeastern Asia such as Malaysia and Indonesia where palm is used. In this case, the benefits of biodiesel utilization are minimized due to the land use change.

Various feedstocks could be utilized depending on climate (temperature range and availability of water) and soil conditions. Subsequently, a more accurate study can be performed such as energy balance of biodiesel production utilizing glycerol for hydrogen production.

Researches concerning hydrogen production utilizing glycerol have been largely performed worldwide; however, reports and works linking hydrogen production utilizing "bioglycerol" and its impact on economy and agriculture were not available yet.

An additional research could be performed to evaluate the "carbon footprint", which denotes environmental impact of a determined activity such as emission of pollutants from production of their feedstocks to hydrogen production system [7].

The dynamics of biohydrogen production as cited in this work can be altered due to the increase of global temperature. Various works have predicted the increase of temperature in various Brazilian regions, which can contribute to increase or decrease or even stop the agricultural production such as coffee in Minas Gerais state, the biggest Brazilian producer [8].

2. Transesterification process

Transesterification is one of the main processes of biodiesel and glycerol production, where one molecule of oil and three molecules of alcohol (methanol or ethanol) allow production of three molecules of ester (biodiesel) and one molecule of glycerol.

Some advantages and disadvantages of both alcohols are depicted in Table 1.

In this work, the utilization of ethanol for transesterification process is also suggested due to high availability and consolidated infrastructure of production, storage, transportation and distribution all over Brazilian territory.

Most of the reports about transesterification reactions indicate higher reactivity with methanol. Hence, most of the biodiesel facilities are utilizing this type of alcohol. However, the trend is to utilize ethanol in Brazil as higher efficiencies are obtained [9].

3. Glycerol chemistry

Studies involving glycerol have occurred only recently due to the increase of its production with the increase of biodiesel production. Taking advantage of its high environmental appeal, various co-products could be obtained as alternative stuffs from synthetic feedstocks, especially petroleum- and coal-based stuffs. A novel term called "glycerolchemistry" was recently adopted by some researchers to evaluate the cited chain [10,11]. The glycerolchemistry is beginning, and to develop its enormous potential, a taskforce must be created.

4. Calculations

The calculations encountered in this work involve glycerol, hydrogen and electricity production. Calculations to obtain amounts of glycerol were performed utilizing the highest performances found in the literature for the cited feedstocks. Most of the presented reactions confirm higher reactivity utilizing methanol.

The calculation of ratios oil/glycerol is based on average content of each oil (which includes different fatty acids) as seen in the work performed by Pousa [12]. In Table 2, values of higher available conversation rates and obtained ratios oil/glycerol are found. How-

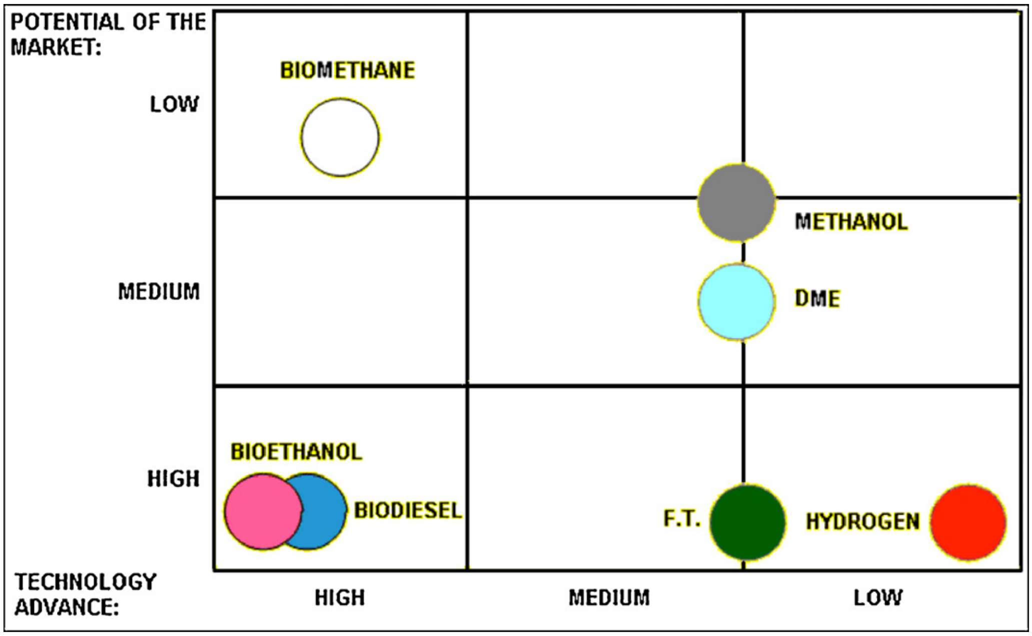

Fig. 1. Characterization of some technologies [1].

Table 1
Advantages and disadvantages of utilization of ethanol and methanol for transesterification process [2].

	Advantages	Disadvantages
Methanol	Lower consumption Higher reactivity Non-hygroscopic	Non-renewable Toxic Non-biodegradable
Ethanol	Higher offer Renewable Biodegradable	Higher consumption Hygroscopic Lower reactivity

ever, ratio oil/glycerol of wastewater was not encountered, being estimated a value of 10.

Various technologies of hydrogen production utilizing glycerol are available, especially thermochemical reactions. The adopted technology for hydrogen production utilizing glycerol is steam reforming, however other reactions could be also performed such as cracking, partial oxidation, aqueous-phase reforming, autothermal reforming or even gasification. The main thermochemical reactions are described below [11]:

Cracking:

$$C_3H_8O_3 \rightarrow 3(CO) + 4(H_2) \qquad \Delta H^\circ = 245\,\text{kJ/mol}$$

Partial oxidation:

$$C_3H_8O_3 + 1.5(O_2) \rightarrow 3(CO_2) + 4(H_2) \qquad \Delta H^\circ = -603\,\text{kJ/mol}$$

Table 2
Higher available conversion rates of transesterification processes and ratios oil/glycerol.

Feedstock	Highest conversion rates	Ratio oil/glycerol
Beef tallow [13]	85.00	11.00
Castor bean [14]	94.00	10.73
Defective coffee [15]	71.95	13.03
Palm [5]	94.30	9.90
Peanut [16]	99.00	9.71
Soybean [16]	99.00	9.58
Wastewater [14]	98.00	10.00

Global steam reforming:

$$C_3H_8O_3(g) + 3(H_2O) \rightarrow 3(CO_2) + 7(H_2) \qquad \Delta H^\circ = 215\,\text{kJ/mol}$$

Aqueous-phase reforming:

$$C_3H_8O_3(l) + 3(H_2O) \rightarrow 3(CO_2) + 7(H_2) \qquad \Delta H^\circ = 123\,\text{kJ/mol}$$

Autothermal reforming:

$$C_3H_8O_3 + O_2 + H_2O \rightarrow 3(CO_2) + 5(H_2) \qquad \Delta H^\circ = -269\,\text{kJ/mol}$$

The study of reactions could be performed through assessment of response reactions (RERs), whose model was developed by Fishtik et al. [17]. For example, the steam reforming could be performed with production of species such as CH_4, CO, solid carbon, and others, not only H_2 ad CO_2. Indeed, it is necessary to determine the number of species to be produced at each reaction.

The steam reforming process was chosen in this work for a more accurate study of hydrogen production utilizing glycerol due to advantages such as high efficiency of hydrogen generation and lower cost of generation. Additional findings could be observed on some reports and works [18].

A physical–chemical analysis was performed by Souza and Silveira [18]. In this work, determined amounts of produced hydrogen were predicted depending on determined thermodynamic conditions. The suggested conditions were reforming at atmospheric pressure and at 700 °C. Following these conditions, to produce 1 Nm^3/h of gaseous hydrogen an amount of 0.948 kg/h of glycerol is necessary if an additional amount of glycerol is utilized to supply heat for steam reforming process since this is an endothermic reaction, i.e., an external supply of heat is necessary to generate reaction. However, if other heat source is utilized, an amount of 0.872 kg/h is necessary.

The electricity could be generated by fuel cells. As syngas from steam reforming process contains high content of gases which are poisonous in low-temperature fuel cells such as PEMFCs (proton exchange membrane fuel cells), the utilization of high-temperature fuel cells such as SOFCs (solid oxide fuel cells) is mandatory. An efficiency of electricity generation of 50% was adopted in the calculations.

Table 3
Production of sugarcane worldwide - data obtained in 2007 [19,20].

Country	Cultivated area (10^3 ha)	(%)	Production (10^6 ton)	(%)
Brazil	5455	27.1	411	31.2
India	4100	20.4	244.8	18.6
China	1316	6.5	93.2	7.1
Thailand	1050	5.2	63.7	4.8
Pakistan	1049	5.2	52.0	3.9
Cuba	700	3.5	24.0	1.8
Mexico	639	3.2	45.1	3.4
Australia	415	2.0	36.0	2.7
Others	5377	26.7	347.1	26.3
Total	20,100	100.0	1.317.9	100.0

Table 4
Production of sugarcane in the most important Brazilian states producers – data obtained in 2005 [22].

State	Production (10^3 ton)	Area (10^3 ha)	Productivity (kg/ha)
São Paulo (SP)	266,071	3085	86.26
Paraná (PR)	34,882	437	79.83
Alagoas (AL)	23,991	397	60.50
Minas Gerais (MG)	31,587	424	74.53
Pernambuco (PE)	18,832	370	50.93
Brazil	422,957	6172	68.53

An annual period of 5000 h was considered since most of feedstocks are not produced all year long.

5. Bioethanol

The production of sugarcane-based-bioethanol in Brazil has been increasing due to demand for automotive purposes. However the utilization of methanol is higher due to higher efficiencies of transesterification detected in various experiments compared with the use of ethanol. As ethanol from sugarcane is renewable and responsible by lower environment impact, the trend in Brazil is a higher utilization of ethanol for this purpose.

Table 3 depicts world leaders in sugarcane production.

Fig. 2 depicts areas of sugarcane cultures in Brazil. In Southeastern and Southern Brazil higher productions of sugarcane and hence sugarcane-based ethanol is encountered. This higher concentration in these regions is due to higher development of ethanol chain in the last three decades for automotive purposes. This consolidated sugarcane and ethanol production (which involves production, storage and distribution) could contribute to the development of FAEE (fatty-acid ethyl ester) chain, i.e., biodiesel utilizing ethanol, with additional production of glycerol.

In regions which concentrates the highest ethanol production, also concentrates the highest production of soybean, peanut, beef tallow, wastewater and utilized edible oil, which allows a major volume of biodiesel production at lower cost mainly due to low cost of transportation of feedstocks, oils, ethanol, and finally FAEE to mix with diesel oil. In other regions, where the highest productions of palm and castor are encountered, an improvement of transportation chain is necessary to get lower cost compared with diesel oil in this way. The production of ethanol in situ is suggested hence avoiding a high environmental impact such as caused by deforestation. The utilization of depleted areas is necessary to confirm the high environmental appeal of this activity.

In Table 4, the production of sugarcane in each state is depicted.

As cited by CTC/Copersucar, 2007 [23], 1 ton of sugarcane is able to produce 75 L if ethanol (better results were encountered attaining 85–90 L), 280 kg of bagasse, and 280 kg of straw (in the case of mechanical harvest). The moisture of bagasse and straw is 50%.

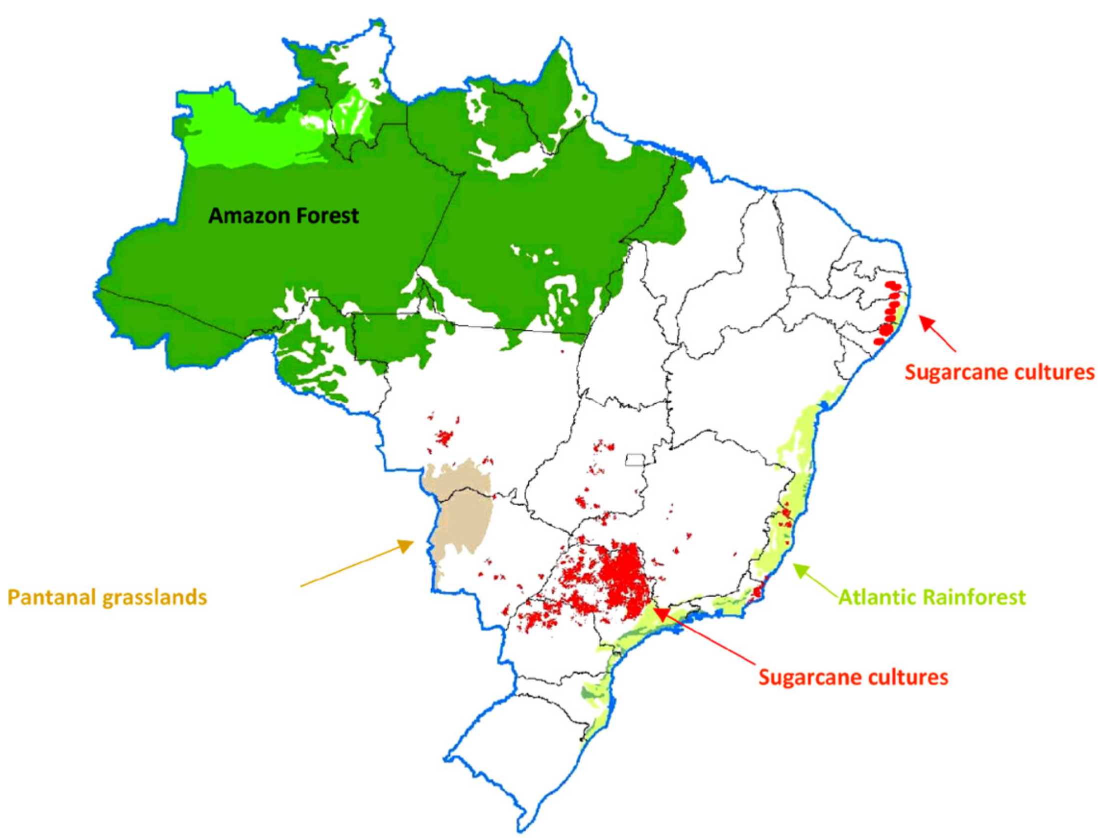

Fig. 2. Areas of sugarcane cultures in Brazil [21].

Table 5
Electricity generation and installed electric power in the Brazilian states [24].

State	Electricity Generation (GWh)	Installed Power (MW)
Paraná (PR)	79,487	15,461
São Paulo (SP)	64,155	13,163
Minas Gerais (MG)	53,411	12,943
Pará (PA)	31,456	6901
Rio de Janeiro (RJ)	25,626	7454
Goiás (GO)	24,465	5249
Bahia (BA)	20,531	5910
Alagoas (AL)	18,402	4014
Rio Grande do Sul (RS)	15,576	4537
Mato Grosso do Sul (MS)	15,538	3127
Santa Catarina (SC)	9871	2641
Sergipe (SE)	9450	1598
Pernambuco (PE)	6473	1558
Amazonas (AM)	6060	1397
Espírito Santo (ES)	6056	1064
Mato Grosso (MT)	5564	2113
Tocantins (TO)	4558	970
Rondônia (RO)	2425	917
Amapá (AP)	946	211
Maranhão (MA)	731	130
Piauí (PI)	654	165
Ceará (CE)	559	1050
Acre (AC)	351	200
Paraíba (PB)	301	59
Distrito Federal (DF)	115	36
Rio Grande do Norte (RN)	112	148
Roraima (RR)	64	144
Brazil	402,937	93,160

For biodiesel production utilizing ethanol, a volume of 3 L of oil for each litre of ethanol were estimated [2].

6. Electricity generation in Brazil

The electricity production utilizing glycerol could also contribute to distributed generation, especially in periods when a minor amount of water is available to hydroelectric generation. This concern is because this is the most important way of electricity generation in Brazil.

Table 5 depicts electricity generation and installed electric power in Brazil.

7. Residues as feedstocks

Various feedstocks encountered in Brazil are currently utilized in transesterification processes. The following residues as feedstocks are cited below. These residues could be utilized due to enormous available volumes.

7.1. Wastewater (scum)

The wastewater, which is especially from domestic origin, is comprised by about 160 g of solid components (scum) for each 200 L of liquid phase. From the scum, 10% is fat [25].

In Brazil, about 60% of the wastewater is collected, and about 30% is treated. The volumes of collected and treated wastewater for each state are cited in Table 6. Beyond utilizing wastewater to produce gray water, biogas and sludge (being that two last products can be utilized for energy purposes) its treatment contributes to the improvement of life quality, and hence avoids illness. The trend is to continue the development of projects concerning collecting and treating of wastewater, also contributing to diversify energy supply [26].

Table 7 depicts annual potentiality of hydrogen and electricity generation utilizing scum obtained in wastewater treatment plants in progress.

Table 6
Volume of wastewater collected and treated in Brazilian states (data collected in 2007) [26].

State	Collected wastewater (m^3/day)	Treated wastewater (m^3/day)
São Paulo (SP)	5,039,477	2,019,536
Rio de Janeiro (RJ)	3,123,248	798,926
Minas Gerais (MG)	2,933,975	152,736
Bahia (BA)	700,285	628,255
Paraná (PR)	456,185	280,481
Rio Grande do Sul (RS)	433,143	95,091
Ceará (CE)	288,031	246,457
Distrito Federal (DF)	276,838	161,537
Goiás (GO)	263,049	81,189
Pernambuco (PE)	196,019	162,565
Paraíba (PB)	191,503	104,721
Espírito Santo (ES)	152,644	88,151
Santa Catarina (SC)	113,504	87,904
Mato Grosso (MT)	74,118	49,393
Maranhão (MA)	62,454	11,200
Sergipe (SE)	50,332	44,584
Rio Grande do Norte (RN)	47,854	22,108
Mato Grosso do Sul (MS)	47,799	46,105
Alagoas (AL)	40,930	10,815
Piauí (PI)	17,950	17,890
Acre (AC)	15,002	–
Amazonas (AM)	12,400	–
Roraima (RR)	11,491	11,491
Pará (PA)	11,020	5539
Amapá (AP)	5162	5022
Rondônia (RO)	3044	2880
Tocantins (TO)	2622	2595
Brazil	14,570,079	5,137,171

7.2. Coffee

Brazil has the highest world coffee production, having higher productions in states of Minas Gerais (MG). Espírito Santo (ES), Paraná (PR) and São Paulo (SP). However, about 20% of national

Table 7
Foreseen energy capacity of scum in the Brazilian states.

State	Utilizing collected wastewater			Utilizing treated wastewater only		
	10^3 Nm^3 H_2	10^3 MWhe	MWe	10^3 Nm^3 H_2	10^3 MWhe	MWe
SP	17,926.73	38.51	7.7	7184.01	15.43	3.09
RJ	11,110.21	23.87	4.77	2841.99	6.11	1.22
MG	10,436.91	22.42	4.48	543.32	1.17	0.23
BA	2491.10	5.35	1.07	2234.87	4.8	0.96
PR	1622.77	3.49	0.7	997.74	2.14	0.43
RS	1540.80	3.31	0.66	338.26	0.73	0.15
CE	1024.60	2.2	0.44	876.71	1.88	0.38
DF	984.78	2.12	0.42	574.63	1.24	0.25
GO	935.73	2.01	0.4	288.81	0.62	0.12
PE	697.29	1.5	0.3	578.29	1.24	0.25
PB	681.23	1.46	0.29	372.52	0.8	0.16
ES	542.99	1.17	0.23	313.58	0.67	0.14
SC	403.76	0.87	0.17	312.7	0.67	0.13
MT	263.66	0.57	0.11	175.7	0.38	0.08
MA	222.17	0.48	0.1	39.84	0.09	0.02
SE	179.04	0.39	0.08	158.6	0.34	0.07
RN	170.23	0.37	0.07	78.64	0.17	0.03
MS	170.03	0.37	0.07	164.01	0.35	0.07
AL	145.6	0.31	0.06	38.47	0.08	0.02
PI	63.85	0.14	0.03	63.64	0.14	0.03
AC	53.37	0.12	0.02	0	0	0
AM	44.11	0.1	0.02	0	0	0
RR	40.88	0.09	0.02	40.88	0.09	0.02
PA	39.2	0.08	0.02	19.7	0.04	0.01
AP	18.36	0.04	0.01	17.86	0.04	0.01
RO	10.83	0.02	0.01	10.24	0.02	0
TO	9.33	0.02	0	9.23	0.02	0
Brazil	51,829.55	111.35	22.27	18,274.25	39.26	7.85

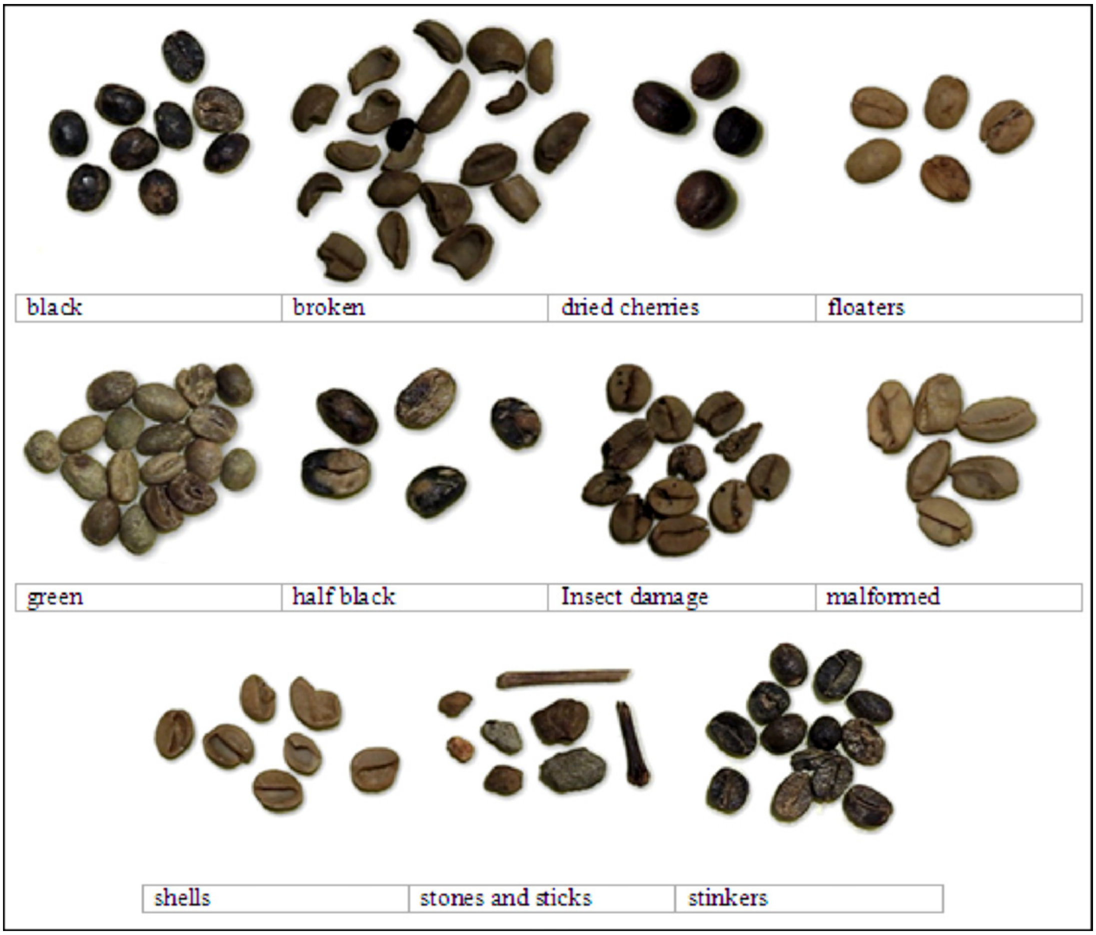

Fig. 3. Types of defective coffee [28].

production of coffee is composed by defective coffee that could be utilized for biodiesel production [15,27].

Fig. 3 depicts main types of defective coffee, which is not utilized for coffee production for drinking purposes but could be utilized for biodiesel production and bioglycerol via transesterification process.

The coffee production in Brazil was comprised by Arabic (76%) and Robust (24%) coffees in 2006 [29].

Fig. 4 depicts distribution of Arabic and Robust coffee in Brazil. Fig. 5 shows distribution of coffee in the world, exclusively in the Tropical macroclimate.

Table 8 shows data about coffee production in Brazilian state in 2008, and impact on hydrogen and electricity production.

Tables 9–14 depict the same data, however, extracted monthly in 2007.

7.3. Beef tallow

A typical Brazilian bovine head has 470 kg as soon as it is killed. About 16 kg of beef tallow per head is extracted [35].

The Brazilian bovine cattle are the second highest in the world (see in Table 15) and the first if considered only cattle to be utilized in the meat chain.

Bovines are widely encountered in Brazilian territory, especially in Mid-Western and Southeastern Brazil. As an example, in the city of Lins (São Paulo State), Bertin (an enterprise that maintain abattoirs) established a biodiesel plant whose capacity is 100,000 ton of beef tallow per year [37]. The foreseen volume of predicted hydrogen to be produced is 30,000 Nm^3 per day, and utilizing a SOFC, the generated energy could attain 64 MWh per day. As seen in this text, an array could be performed with objective to optimize energy generation and utilization in the biodiesel plant and abattoirs as a whole.

Table 16 depicts the utilization of the land in Brazil.

The capacity of energy generation utilizing beef tallow in each state is cited in Table 17.

An attention must be paid to the increase in the price of tallow beef, which is currently utilized in the production of soaps [39].

8. Other feedstocks

Among vegetable feedstocks widely utilized in Brazil, the main one is soybean, having palm and castor bean as other important feedstocks. Other feedstocks such as sunflower seed, peanut, babassu and others can be utilized in the near future, taking advantage their potentialities.

Last year, an enormous attention was paid to the development of biodiesel chain, especially using castor. This preference was paid due to its high productivity in Brazil and also due to high social impact. These facts were also verified utilizing vegetable feedstocks such as palm (especially in Northern Brazil), babassu (obtained through extractivism way in states such as Maranhão and Piauí), wastewater, utilized edible oil and beef tallow. Other advantage of castor bean is the possibility of development of joint cultures such as green bean, peanut or maize. However, with high social impact paid by these feedstocks, a higher biodiesel production in Brazil is given by soybean due to its low cost, beyond soybean culture is the main Brazilian culture in terms of area. However, the social

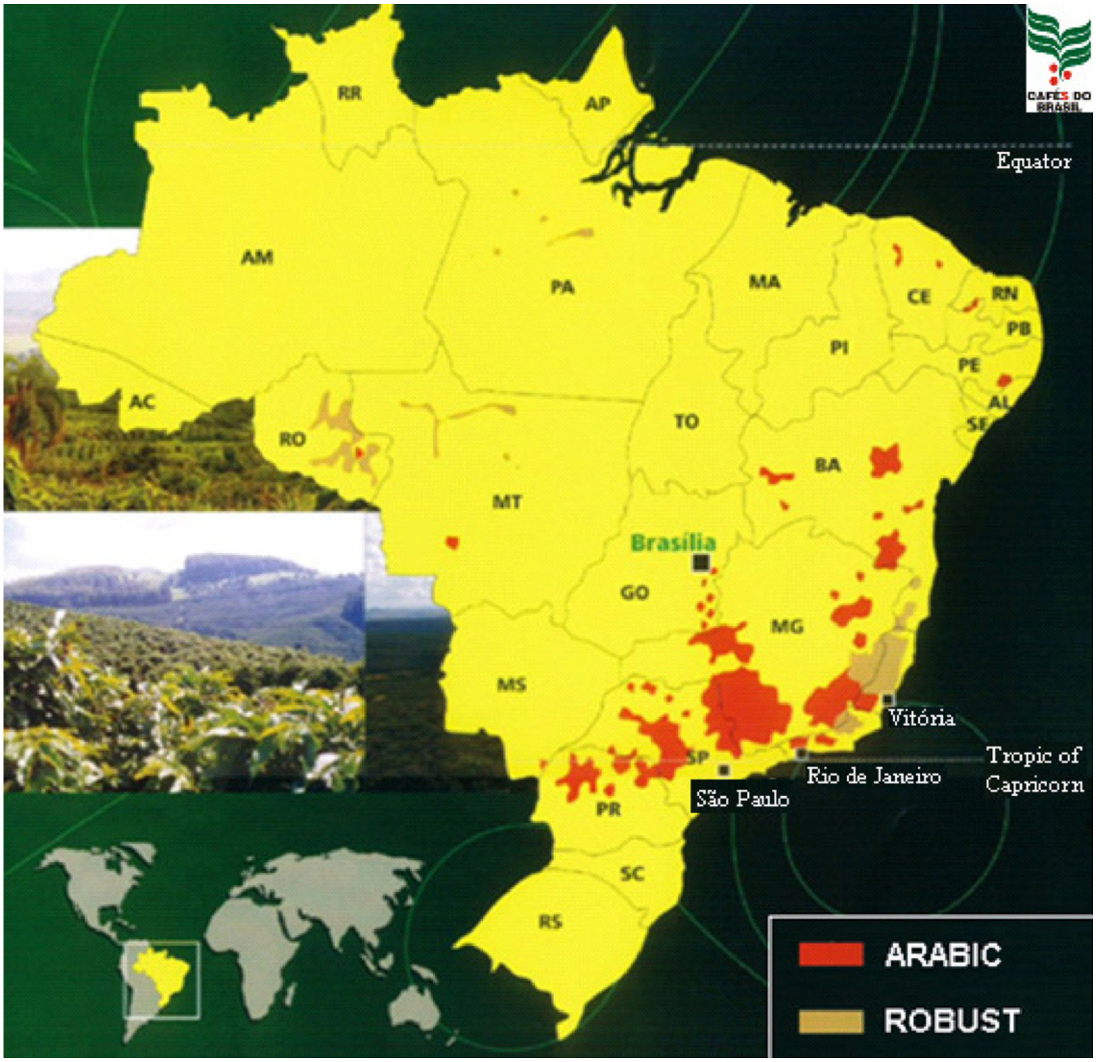

Fig. 4. Distribution of coffee in Brazil [30].

impact and productivity (oil production per area) is much lower [40]. In 2007, 59% of produced biodiesel came from soybean, 26% came from castor bean, and 15% came from other feedstocks [40].

In Europe, the main vegetable feedstock is canola, which has productivity between 350 and 400 kg of oil per hectare, satisfactory for European conditions [8].

Table 18 depicts the cultivated area in Brazil. The first culture is soybean, which is utilized especially for production of edible oils, consumption *in natura* and for feed, having other cultures such as sugarcane which supplies ethanol. Transesterification process is a recent activity in Brazil with enormous potential to increase. Obviously, the production of soybean, sugarcane, castor bean, peanuts, and others will increase enormously.

Table 19 depicts values of vegetable oil production in Brazil.

The order of feedstocks (seen in Table 18) and percentage is near that observed in transesterification processes, where the main feedstock is also soybean.

Table 20 shows the content of oil of main biodiesel and glycerol feedstocks.

Various estimations have been performed to evaluate the potential of utilization of each plant in Brazil. The utilization of jatropha is recent, and in Brazil, the potential is enormous since this plant could be utilized in various Brazilian regions, inclusively arid regions such as Northeastern Brazil. About 40 millions of hectares are able to be utilized for this purpose [41].

In Fig. 6, regions with high potential of development of jatropha were cited.

The potential of the palm is Brazil is high. The actual utilized area in Brazil is about 60,000 ha, however, the able area is 100 times higher (considering depleted areas only) [8]. This plant is usually localized in regions where high indexes of pluviosity and high temperatures during the year are encountered (such as Equatorial climate in Brazil, localized in the North region), as seen in Fig. 7.

About 70% of depleted area previously occupied by Amazon Jungle is used for cattle, generally at very low density of heads. One part of this depleted area is also occupied by soybean production. An attention must being paid to avoid disruptions in terms of commerce of products such as meat, soybean and its derivatives such as biodiesel and glycerol. The main argument is the fact of environmentally friendly stuff that is generated with high environmental impact [43–45].

Some plants such as peanut could be utilized to recovery nitrogen utilized in the sugarcane culture and to avoid erosion in periods when soil is not utilized. Brazil has the highest world production of sugarcane, and the potential of peanut production is enormous. Other cultures could be utilized such as soybean.

In the case of some regions of Southeastern Brazil, the productivity and revenue paid by peanut also allow the wide development of this culture. In São Paulo State, which has the highest Brazil-

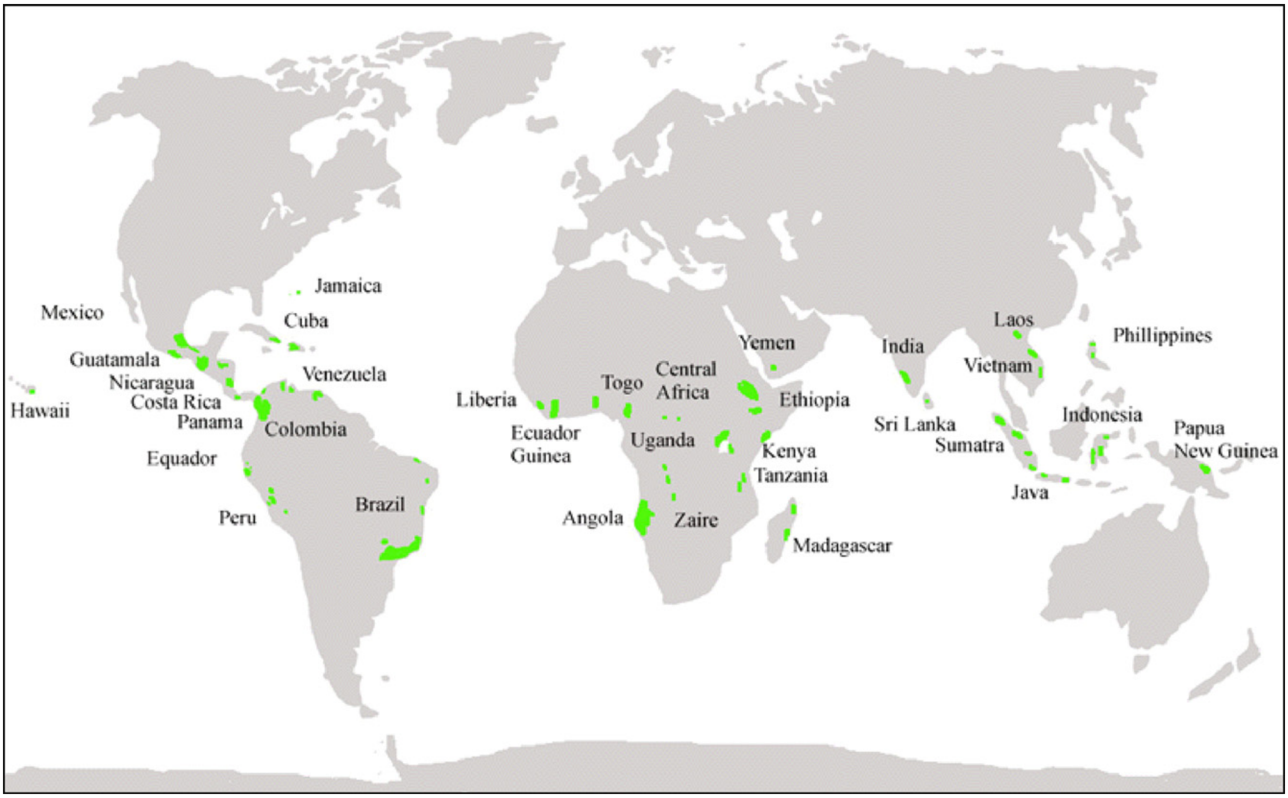

Fig. 5. Distribution of coffee in the world [31].

Table 8
Energy capacity of harvested coffee in some Brazilian states [32–34].

State	Harvested area (ha)	Quantity (ton)	Productivity (ton/ha)	Defective coffee (ton)	Glycerol (ton)	H_2 (Nm^3)	MWhe	Average kWe
MG	1,078,708	1,228,124	1139	245,625	1874.06	1,890,073	4060.59	812.12
ES	536,591	514,263	0.958	102,853	784.74	791,447	1700.33	340.07
SP	219,800	258,370	1175	51,674	394.26	397,630	854.26	170.85
RO	171,168	101,676	0.594	20,335	155.15	156,478	336.17	67.23
BA	147,934	129,651	0.876	25,930	197.84	199,532	428.67	85.73
PR	116,759	148,257	1.27	29,651	226.23	228,166	490.18	98.04
MT	34,517	18,559	0.538	3712	28.32	28,563	61.36	12.27
PA	18,768	20,697	1103	4139	31.58	31,853	68.43	13.69
RJ	13,908	15,494	1114	3099	23.64	23,845	51.23	10.25
GO	7799	14,235	1825	2847	21.72	21,908	47.06	9.41
CE	7493	2461	0.328	492	3.76	3787	8.14	1.63
PE	4987	3080	0.618	616	4.70	4740	10.18	2.04
AC	3677	2533	0.689	507	3.86	3898	8.38	1.68
MS	2459	4708	1915	942	7.18	7245	15.56	3.11
AM	2450	2544	1038	509	3.88	3916	8.41	1.68
DF	918	904	0.985	181	1.38	1391	2.99	0.60
TO	70	126	1.8	25	0.19	194	0.42	0.08
PB	26	27	1038	5	0.04	41	0.09	0.02
AL	8	1	0.125	0	0.00	2	0.00	0.00
Brazil	2,368,040	2,465,710	1007	493,142	3762.55	3,794,709	8152.46	1630.49

Table 9
Amount of harvested coffee in the main Brazilian states monthly (ton) [32–34].

State	April	May	June	July	August	September	October	Total
MG	25,368	126,852	228,336	253,704	317,130	253,704	63,426	1,268,520
ES	43,254	216,264	178,416	70,284	21,624	10,812	930	541,584
SP	0	26,820	107,280	80,460	34,866	18,774	0	268,200
PR	8046	17,238	35,802	41,106	23,868	10,608	0	136,668
BA	13,410	20,154	26,868	33,588	33,588	6720	0	134,328
RO	12,576	27,510	32,226	5502	786	0	0	78,600
PA	4212	7686	6408	0	0	0	0	18,306
RJ	3168	7920	3168	1584	0	0	0	15,840
MT	3000	6750	5250	0	0	0	0	15,000
Others	2232	4464	7812	6696	1116	0	0	22,320
Brazil	115,266	461,658	631,566	492,924	432,978	300,618	64,356	2,499,366

Table 10
Amount of defective coffee in the main Brazilian states monthly (ton).

State	April	May	June	July	August	September	October	Total
MG	5074	25,370	45,667	50,741	63,426	50,741	12,685	253,704
ES	8651	43,253	35,683	14,057	4325	2162	186	108,317
SP	0	5364	21,456	16,092	6973	3755	0	53,640
PR	1609	3448	7160	8221	4774	2122	0	27,334
BA	2682	4031	5374	6718	6718	1344	0	26,866
RO	2515	5502	6445	1100	157	0	0	15,720
PA	842	1537	1282	0	0	0	0	3661
RJ	634	1584	634	317	0	0	0	3168
MT	600	1350	1050	0	0	0	0	3000
Others	446	893	1562	1339	223	0	0	4464
Brazil	23,053	92,332	126,313	98,589	86,596	60,124	12,871	499,873

Table 11
Foreseen glycerol production (in ton).

State	April	May	June	July	August	September	October	Total
MG	30.88	154.38	277.88	308.75	385.54	308.75	76.79	1542.17
ES	52.25	262.83	216.92	85.50	26.13	13.46	0.79	658.67
SP	0.00	32.46	130.63	98.17	42.75	22.96	0.00	326.17
PR	9.50	20.58	43.54	49.88	29.29	12.67	0.00	166.25
BA	16.63	24.54	32.46	41.17	41.17	7.92	0.00	163.08
RO	15.04	33.25	38.79	6.33	0.79	0.00	0.00	95.79
PA	4.75	9.50	7.92	0.00	0.00	0.00	0.00	22.17
RJ	3.96	9.50	3.96	1.58	0.00	0.00	0.00	19.00
MT	3.96	7.92	6.33	0.00	0.00	0.00	0.00	18.21
Others	2.38	5.54	9.50	7.92	1.58	0.00	0.00	26.92
Brazil	140.13	561.29	767.92	599.29	526.46	365.75	78.38	3038.42

Table 12
Foreseen hydrogen production (in Nm^3).

State	April	May	June	July	August	September	October	Total
MG	32,534	162,687	292,839	325,373	406,717	325,373	81,344	1,626,869
ES	55,473	277,357	228,817	90,139	27,733	13,866	1193	694,578
SP	0	34,396	137,586	103,190	44,716	24,078	0	343,965
PR	10,319	22,107	45,916	52,718	30,611	13,605	0	175,276
BA	17,198	25,847	34,458	43,076	43,076	8618	0	172,275
RO	16,129	35,281	41,330	7056	1008	0	0	100,804
PA	5402	9857	8218	0	0	0	0	23,478
RJ	4063	10157	4063	2031	0	0	0	20,315
MT	3848	8657	6733	0	0	0	0	19,238
Others	2863	5725	10,019	8587	1431	0	0	28,625
Brazil	147,828	592,073	809,980	632,172	555,292	385,541	82,536	3,205,421

ian production, this culture could be applied between October and February [20].

As said Rodrigues [20], two thirds of the area traditionally utilized by sugarcane could also be utilized for other cultures (via rotation), being that, in this selected area, 20% could be utilized for peanut culture (which has a potential to attain 4 ton/ha), and 80% could be utilized for soybean culture (which has a potential to attain 3 ton/ha). Cultures of peanut and soybean could be developed out of period of sugarcane (especially between December and March in Mid-Western, Southeastern and Southern Brazil) [20,22].

Table 21 shows the production of peanut in Brazil and São Paulo state [46].

São Paulo State has the highest peanut and ethanol productions, which contributes to develop the biodiesel and

Table 13
Foreseen electricity generation (in MWh).

State	April	May	June	July	August	September	October	Total
MG	69.67	349.13	629.38	699.04	874.00	699.04	174.96	3495.21
ES	119.54	596.13	491.63	193.96	59.38	30.08	2.38	1492.29
SP	0.00	73.63	295.29	221.67	95.79	51.46	0.00	738.63
PR	22.17	47.50	98.96	113.21	65.71	29.29	0.00	376.83
BA	37.21	55.42	74.42	92.63	92.63	18.21	0.00	370.50
RO	34.83	76.00	88.67	15.04	2.38	0.00	0.00	216.92
PA	11.88	21.38	17.42	0.00	0.00	0.00	0.00	50.67
RJ	8.71	22.17	8.71	4.75	0.00	0.00	0.00	43.54
MT	7.92	18.21	14.25	0.00	0.00	0.00	0.00	41.17
Others	6.33	12.67	21.38	18.21	3.17	0.00	0.00	61.75
Brazil	317.46	1272.21	1740.08	1358.50	1193.04	828.08	177.33	6886.71

Table 14
Foreseen average electricity generation (in kW).

State	April	May	June	July	August	September	October	Total
MG	13.98	69.90	125.83	139.81	174.75	139.81	34.95	699.03
ES	23.84	119.17	98.32	38.73	11.91	5.96	0.51	298.44
SP	0.00	14.78	59.11	44.34	19.21	10.35	0.00	147.80
PR	4.43	9.50	19.73	22.65	13.15	5.84	0.00	75.31
BA	7.39	11.11	14.80	18.51	18.51	3.71	0.00	74.02
RO	6.93	15.16	17.76	3.03	0.44	0.00	0.00	43.31
PA	2.32	4.24	3.53	0.00	0.00	0.00	0.00	10.09
RJ	1.75	4.36	1.75	0.87	0.00	0.00	0.00	8.73
MT	1.65	3.72	2.89	0.00	0.00	0.00	0.00	8.27
Others	1.23	2.46	4.31	3.69	0.62	0.00	0.00	12.30
Brazil	63.52	254.40	348.02	271.63	238.59	165.66	35.47	1377.29

Table 15
Biggest bovine cattles in 2007 [36].

Country	Heads (10^6)	(%)
India	282	28.31
Brazil	180	18.10
China	139	13.99
United States	97	9.74
European Union	88	8.86
Argentina	51	5.14
Australia	29	2.87
Mexico	26	2.64
Russia	19	1.91
South Africa	14	1.40
Canada	14	1.42
Others	56	5.61
Total	996	100.00

Table 16
Amount of utilized areas in Brazil [38].

Utilization of the land (10^6 ha)	
Overall area occupied by all human activities	354.9
Overall area occupied by cattle in general	172.3
Overall area occupied by bovines	169.9

glycerol chain utilizing both stuffs, and hence, diminishing their costs.

As cited above, soybean could also be utilized to supply nitrogen, highly utilized by sugarcane, taking advantage of the consolidated infrastructure of storage and transportation and knowledge obtained in the last years. The increase in productivity of this plant has been high, being the main feedstock of biodiesel in Brazil. The productivity of peanut is similar to that obtained by soybean (whose production also is observed in Table 22 and in Fig. 8), having a high potential of biodiesel and glycerol production.

Despite technical problems recently encountered in castor-based biodiesel (such as high viscosity and high cost of production), an area of 4.5 millions of hectares is able to cultivate. Other varieties of castor must be developed with objective to produce a more adequate oil to attain technical specifications [34].

Table 17
Foreseen energy capacity of beef tallow in Brazilian states in 2005 [38].

Brazil: Bovines						
State	Amount of bovines (10^3 heads)	Killed bovines (10^3 heads)	Glycerol production (ton)	Hydrogen production (10^3 Nm^3 H_2)	Generated electricity (MWhe)	Electric potential (kWe)
MT	26,652	5277	8945	9571	20,561	4112
MS	24,504	4852	8224	8800	18,905	3781
MG	21,404	4238	7184	7686	16,513	3303
GO	20,727	4104	6956	7443	15,990	3198
PA	18,064	3577	6063	6487	13,936	2787
RS	14,240	2820	4779	5114	10,986	2197
SP	13,421	2657	4504	4819	10,354	2071
RO	11,349	2247	3809	4076	8756	1751
BA	10,463	2072	3512	3757	8072	1614
PR	10,153	2010	3408	3646	7833	1567
TO	7962	1576	2672	2859	6143	1229
MA	6449	1277	2164	2316	4975	995
SC	3377	669	1133	1213	2605	521
AC	2313	458	776	831	1785	357
CE	2299	455	772	826	1774	355
RJ	2093	414	702	752	1615	323
ES	2027	401	680	728	1564	313
PE	1909	378	641	686	1473	295
PI	1827	362	613	656	1409	282
AM	1197	237	402	430	924	185
PB	1053	208	353	378	812	162
SE	1005	199	337	361	775	155
AL	985	195	331	354	760	152
RN	978	194	328	351	755	151
RR	507	100	170	182	391	78
DF	102	20	34	37	79	16
AP	97	19	32	35	75	15
Brazil	207,157	41,017	69,527	74,391	159,819	31,964

Table 18
Cultivated area of main cultures available in Brazil in 2006 [4,37].

Culture	Cultivated area (ha)	(%)
Soybean	21,958,076	28.63
Maize	12,610,766	16.44
Sugarcane	6,185,681	8.07
Green bean	4,012,367	5.23
Rice	2,969,290	3.87
Coffee	2,327,813	3.04
Cassava	1,874,198	2.44
Wheat	1,541,354	2.01
Cotton	898,650	1.17
Orange	803,027	1.05
Sorghum	702,485	0.92
Cocoa	634,616	0.83
Oat	305,456	0.40
Potato	140,804	0.18
Castor	137,580	0.18
Peanut	106,177	0.14
Triticale	97,801	0.13
Barley	81,126	0.11
Other cultures	19,760,057	25.17
Total	76,697,324	100.00

Table 19
Production of vegetable oils in Brazil [4].

Culture	Production of oils (10^6 ton)	(%)
Soybean	5571	89.2
Cotton (seed)	268.4	4.3
Palm	140.0	2.2
Sunflower	74.6	1.2
Maize	63.6	1.0
Castor bean	60.8	1.0
Rapeseed	22.8	0.4
Peanut	21.8	0.3
Palm kernel	15.8	0.3
Linseed	2.1	<0.1
Coconut	1.9	<0.1
Total	6242.8	100.0

Table 23 shows production of castor bean in Brazil and Bahia state, where the highest Brazilian production is encountered. However, a higher productivity of castor bean could be attained whether consolidated researches are developed since productivity of 2000 kg/ha is possible [33].

Table 20
Some feedstocks for biodiesel production encountered in Brazil [4].

Feedstock	Region[a]	Oil content (%)
Andiroba	N	28
Babassu	N, NE	50
Brazil nut	N	50
Buriti	N	20
Canola	S	38
Castor bean	S, SE, MW, NE	52
Coffee	S, SE, MW, N, NE	9.5
Cotton (seed)	S, SE, MW, NE	18
Jatropha	SE, MW, NE	52
Linseed	S	33
Macauba	SE, MW, N, NE	18
Palm	N, NE	22
Passion fruit (seed)	SE, MW, NE	10
Peanut	SE	44
Pequi	SE, MW, NE	25
Rapeseed	S	45
Sesame	NE, SE	52
Soybean	S, SE, CO, N, NE	19
Sunflower	S, SE, MW	40

[a] N: North; NE: Northeast; MW: Mid-West; SE: Southeast; S: South.

Table 21
Peanut production in São Paulo state and in Brazil [46].

State	Production (10^3 ton)	Harvested area (10^3 ha)	Average productivity (kg/ha)
São Paulo (SP)	226.10	89.60	2523.44
Brazil	314.91	135.83	2318.32

Table 22
Soybean production and the highest Brazilian producers [33].

State	Production (10^3 ton)	Harvested area (10^3 ha)	Average productivity (kg/ha)
Mato Grosso (MT)	17,761	6107	2909
Paraná (PR)	9492	4155	2285
Goiás (GO)	6984	2663	2622
Mato Grosso do Sul (MS)	3719	2025	1836
Minas Gerais (MG)	2937	1119	2625
Brazil	51,182	22,949	2230

Table 24 depicts production ratio of each feedstock. Tables 25–28 depict amount of produced glycerol, hydrogen, electricity and average power per hectare, respectively, devoted by some feedstocks depending on the region and month when these feedstocks are harvested, from January (J) to December (D). These data were based on obtained information of 2005.

The trend is to increase the values of productivities of cited cultures. The overwhelming increase of sugarcane culture (especially for production of ethanol as a fuel) also allows the increase of peanut and soybean via rotation of cultures.

9. H-BIO

Recently, PETROBRAS (Petróleo Brasileiro S.A.), a Brazilian company, developed a novel fuel called H-BIO. This fuel comes from a reaction between bio-oil and hydrogen, which could be produced by steam reforming of glycerol cited in this work. Beyond H-BIO, “biopropane” production is detected, whose fuel is constituent of LPG (liquefied petroleum gas) [47].

The obtained volumes of products are cited below [47]:

$$100\,\mathrm{L}\ \text{bio-oil} + 35\,\mathrm{Nm}^3\ \mathrm{H_2} = 96\,\mathrm{L}\ \text{of}\ \text{H-BIO} \\ +2.2\,\mathrm{Nm}^3\ \text{of}\ \text{propane}$$

The potential of H-BIO and “biopropane” production are depicted in Tables 29 and 30 respectively, from January (J) to December (D).

10. Potential of hydrogen production and electricity generation utilizing glycerol

In this topic, the amount of hydrogen production and electricity generation utilizing glycerol was evaluated. Utilizing residues, the amount of collected wastewater, defective coffee and beef tallow were considered. These values were cited above.

The highest potential of biodiesel and bioglycerol production is devoted by palm. As cited previously the potential is 60 million of hectares [34]. The potential of soybean was based on areas traditionally utilized by sugarcane (as cited above, 80% of sugarcane area is able for rotation) and areas able to be obtained from bovines whether its density increases to two heads per hectare although as cited previously this density could be increased to eight heads per hectare with additional investments [6,20]. The choice of two

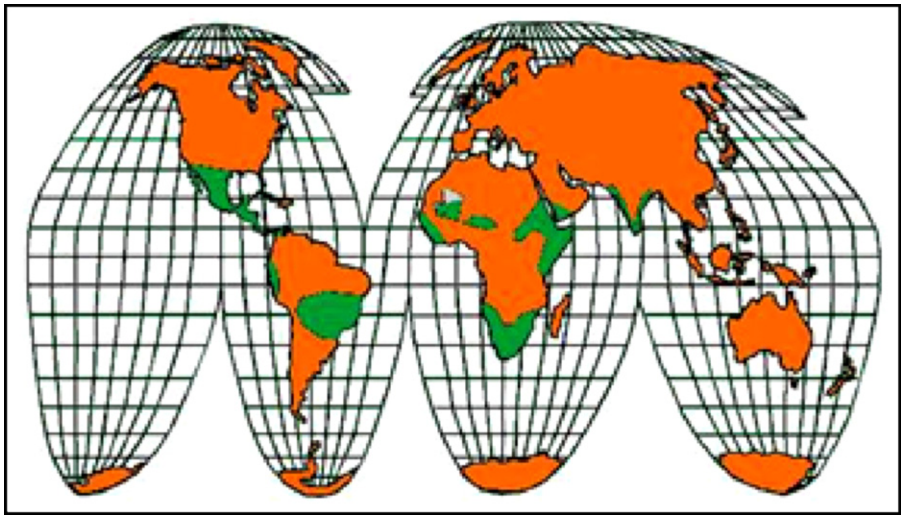

Fig. 6. Regions where jatropha culture could be developed [42].

Table 23
Production of castor bean in Brazil and in the state of Bahia [33].

State	Production (10^3 ton)	Harvested area (10^3 ha)	Average productivity (kg/ha)
Brazil	168	231	728
Bahia (BA)	132	182	725

heads per hectare is conservative since it depends on availability of infrastructure. Basing on these assumptions, the additional area to be utilized by soybean is about 8.18 million of hectares. In the case of castor bean, as cited previously, the potential of utilization plus area currently utilized is 4.5 million of hectares [34]. And as cited previously, the suggested area to be utilized by peanut is 0.91 million of hectares [20].

Table 31 depicts potential of hydrogen and electricity generation basing on assumptions cited in this work.

Considering the cited assumptions, the potential of electricity generation is 56,468 GWh, i.e., 14% of electricity generation in Brazil in 2005. Most of the potential is devoted by palm. Other feedstocks are responsible by less than 1% of electricity generation, however this feedstocks could contribute to supply energy in own facilities such as abattoirs (utilizing beef tallow) and wastewater treatment plant (utilizing scum from wastewater). Additionally, some feedstocks such as cotton seed and peanut without irrigation could be harvested in a period of lower pluviosity being an alternative to hydroelectric power plants, the main way of Brazilian electricity generation. This period (in most of Brazilian regions, where Tropical climate is encountered) is between May and August.

In Amazon jungle, where palm is encountered, the energy generation utilizing glycerol from palm oil could contribute for a decentralized generation in a region where small cities and villages generate electricity utilizing internal combustion engines whose fuel is petroleum-based diesel, a non-renewable source

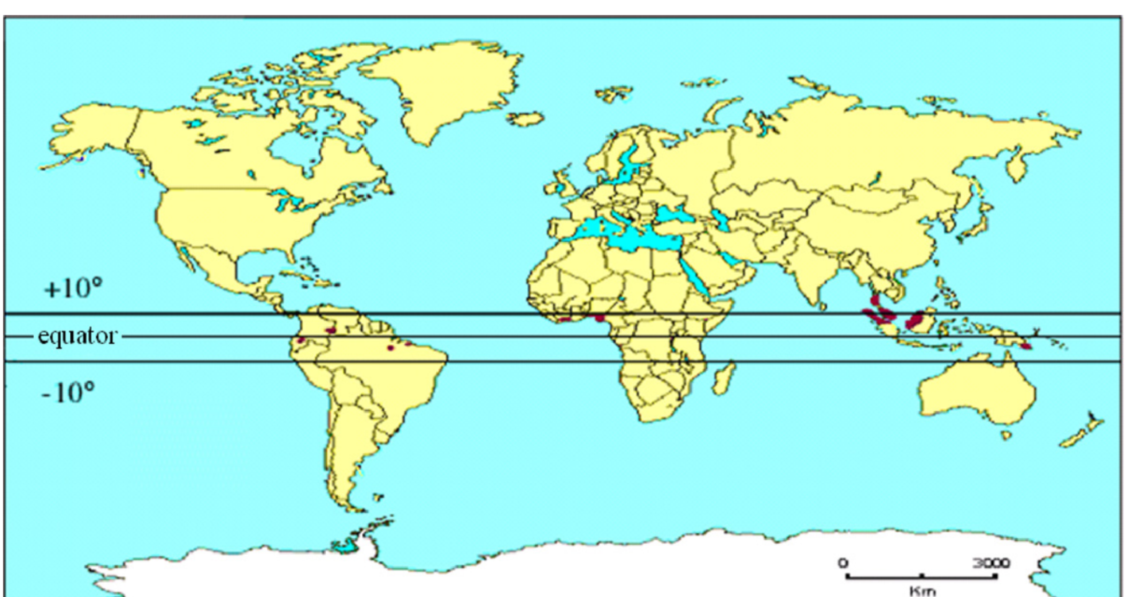

Fig. 7. Areas of production of palm oil [4].

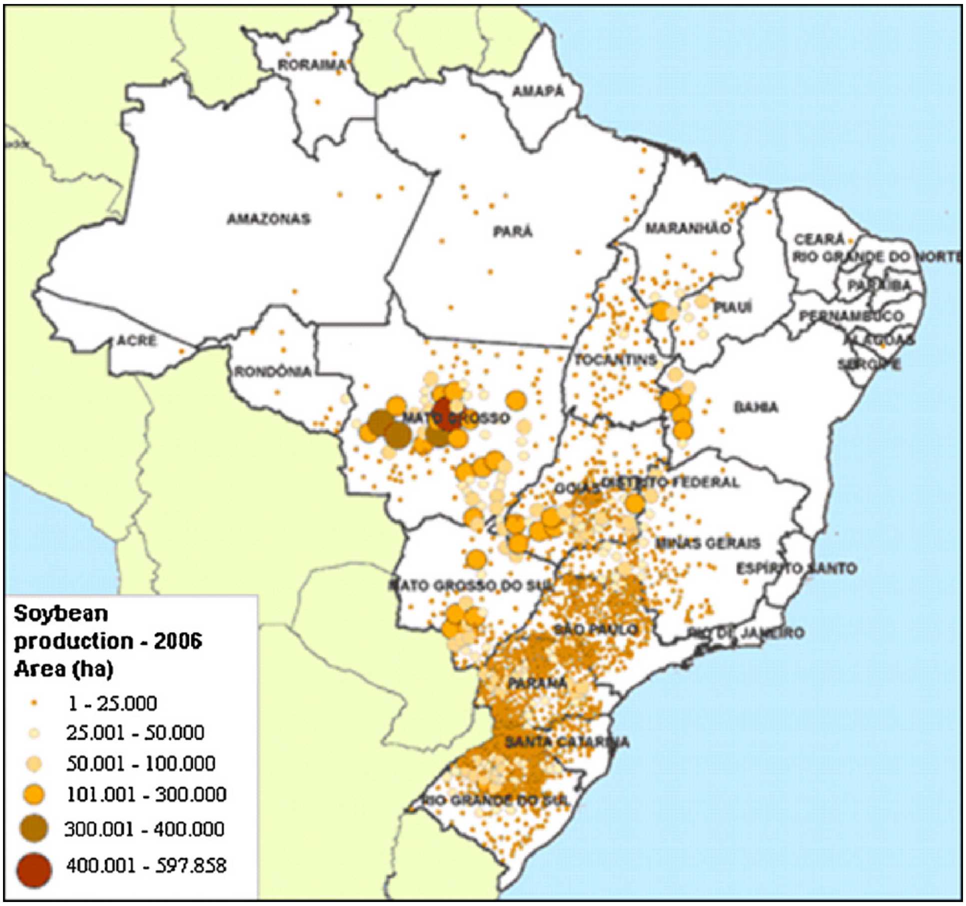

Fig. 8. Distribution of soybean in Brazil [34].

Table 24
Production ratio of each feedstock depending on region and month [34].

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D
Production ratio (%)	S	Soybean	15.5	32.8	34.5	17.2	0	0	0	0	0	0	0	0
	SE	Soybean	0	20.5	39.2	29.5	10.8	0	0	0	0	0	0	0
		Peanut with irrigation	16.2	33.1	33.8	16.9	0	0	0	0	0	0	0	0
		Peanut without irrigation	0	0	0	0	12.1	44.3	36.5	7.1	0	0	0	0
	MW	Soybean	4.3	23.5	42.1	24.4	5.8	0	0	0	0	0	0	0
	NE	Soybean	0	14.5	36.9	33	13.1	2.6	0	0	0	0	0	0
		Castor bean	23.6	47.6	25	1.9	1	0.4	0.3	0.2	0	0	0	0
	N	Soybean	0	27.2	43.3	22.8	6.7	0	0	0	0	0	0	0
		Palm	10	9	10	9	12	9	8	7.5	6.5	5.5	4.5	9
		Medium	6.33	18.9	24.2	14.6	9.13	10.7	10.3	3.28	0.79	0.54	0.44	0.82

Table 25
Amount of produced glycerol per hectare of each feedstock.

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D	Total
kg glycerol/ha	S	Soybean	5.64	11.9	12.5	6.25	0	0	0	0	0	0	0	0	36.36
	SE	Soybean	0	9.12	17.4	13.1	4.8	0	0	0	0	0	0	0	44.49
		Peanut with irrigation	13.7	28	28.6	14.3	0	0	0	0	0	0	0	0	84.67
		Peanut without irrigation	0	0	0	0	10.2	37.5	30.9	6.01	0	0	0	0	84.67
	MW	Soybean	1.96	10.7	19.2	11.1	2.64	0	0	0	0	0	0	0	45.58
	NE	Soybean	0	7.4	18.8	16.8	6.69	1.33	0	0	0	0	0	0	51.11
		Castor bean	14.8	29.9	15.7	1.19	0.63	0.25	0.19	0.13	0	0	0	0	62.89
	N	Soybean	0	13.2	21	11	3.24	0	0	0	0	0	0	0	48.43
		Palm	39.9	35.9	39.9	35.9	47.9	35.9	31.9	29.9	25.9	22	18	35.9	399.09

Table 26
Amount of produced hydrogen per hectare of each feedstock.

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D	Total
Nm^3 H_2/ha	S	Soybean	5.95	12.6	13.2	6.6	0	0	0	0	0	0	0	0	38.36
	SE	Soybean	0	9.62	18.4	13.8	5.07	0	0	0	0	0	0	0	46.93
		Peanut with irrigation	14.5	29.6	30.2	15.1	0	0	0	0	0	0	0	0	89.31
		Peanut without irrigation	0	0	0	0	10.8	39.6	32.6	6.34	0	0	0	0	89.31
	MW	Soybean	2.07	11.3	20.2	11.7	2.79	0	0	0	0	0	0	0	48.08
	NE	Soybean	0	7.81	19.9	17.8	7.06	1.4	0	0	0	0	0	0	53.91
		Castor bean	15.7	31.6	16.6	1.26	0.66	0.27	0.2	0.13	0	0	0	0	66.34
	N	Soybean	0	13.9	22.1	11.6	3.42	0	0	0	0	0	0	0	51.08
		Palm	42.1	37.9	42.1	37.9	50.5	37.9	33.7	31.6	27.4	23.2	18.9	37.9	420.98

Table 27
Amount of produced electricity per hectare of each feedstock.

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D	Total
MWhe/ha	S	Soybean	0.01	0.03	0.03	0.01	0	0	0	0	0	0	0	0	0.08
	SE	Soybean	0	0.02	0.04	0.03	0.01	0	0	0	0	0	0	0	0.10
		Peanut with irrigation	0.03	0.06	0.06	0.03	0	0	0	0	0	0	0	0	0.19
		Peanut without irrigation	0	0	0	0	0.02	0.08	0.07	0.01	0	0	0	0	0.19
	MW	Soybean	0	0.02	0.04	0.03	0.01	0	0	0	0	0	0	0	0.10
	NE	Soybean	0	0.02	0.04	0.04	0.02	0	0	0	0	0	0	0	0.12
		Castor bean	0.03	0.07	0.04	0	0	0	0	0	0	0	0	0	0.14
	N	Soybean	0	0.03	0.05	0.03	0.01	0	0	0	0	0	0	0	0.11
		Palm	0.09	0.09	0.09	0.08	0.11	0.08	0.07	0.07	0.06	0.05	0.04	0.08	0.91

Table 28
Average power per hectare of each feedstock.

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D	Total
Average kWe/ha	S	Soybean	0	0.01	0.01	0	0	0	0	0	0	0	0	0	0.016
	SE	Soybean	0	0	0.01	0.01	0	0	0	0	0	0	0	0	0.020
		Peanut with irrigation	0.01	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0.038
		Peanut without irrigation	0	0	0	0	0	0.02	0.01	0	0	0	0	0	0.038
	MW	Soybean	0	0	0.01	0.01	0	0	0	0	0	0	0	0	0.021
	NE	Soybean	0	0	0.01	0.01	0	0	0	0	0	0	0	0	0.023
		Castor bean	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0	0.029
	N	Soybean	0	0.01	0.01	0.01	0	0	0	0	0	0	0	0	0.022
		Palm	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.181

Table 29
Volumes of production of H-BIO.

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D	Total
Litres H-BIO/ha	S	Soybean	48.6	103	108	54	0	0	0	0	0	0	0	0	314
	SE	Soybean	0	78.7	150	113	41.5	0	0	0	0	0	0	0	384
		Peanut with irrigation	164	334	341	171	0	0	0	0	0	0	0	0	1010
		Peanut without irrigation	0	0	0	0	122	448	369	71.7	0	0	0	0	1010
	MW	Soybean	16.9	92.2	165	95.8	22.8	0	0	0	0	0	0	0	393
	NE	Soybean	0	63.8	162	145	57.7	11.4	0	0	0	0	0	0	441
		Castor bean	79.1	160	83.8	6.37	3.35	1.34	1.01	0.67	0	0	0	0	335
	N	Soybean	0	114	181	95.3	28	0	0	0	0	0	0	0	418
		Palm	295	266	295	266	354	266	236	221	192	162	133	266	2951

Table 30
Volumes of production of propane.

	Region	Culture	J	F	M	A	M	J	J	A	S	O	N	D	Total
Nm^3 propane/ha	S	Soybean	1.07	2.26	2.38	1.19	0	0	0	0	0	0	0	0	6.90
	SE	Soybean	0	1.73	3.31	2.49	0.91	0	0	0	0	0	0	0	8.45
		Peanut with irrigation	3.6	7.36	7.51	3.76	0	0	0	0	0	0	0	0	22.22
		Peanut without irrigation	0	0	0	0	2.69	9.85	8.11	1.58	0	0	0	0	22.22
	MW	Soybean	0.37	2.03	3.64	2.11	0.5	0	0	0	0	0	0	0	8.64
	NE	Soybean	0	1.4	3.57	3.19	1.27	0.25	0	0	0	0	0	0	9.69
		Castor bean	1.74	3.51	1.84	0.14	0.07	0.03	0.02	0.01	0	0	0	0	7.38
	N	Soybean	0	2.5	3.98	2.1	0.62	0	0	0	0	0	0	0	9.19
		Palm	6.49	5.84	6.49	5.84	7.79	5.84	5.19	4.87	4.22	3.57	2.92	5.84	64.92

Table 31
Potential of hydrogen production and electricity generation in Brazil.

Feedstock	Hydrogen production (10^6 Nm^3)	Electricity generation (GWhe)	(%)
Treated wastewater	18.27	39.26	0.010
Collected wastewater	51.83	111.35	0.028
Defective coffee	3.79	8.15	0.002
Beef tallow	74.39	159.82	0.040
Castor bean	293.24	630.00	0.156
Palm	25,414.57	54,600.00	13,551
Peanut	80.40	172.74	0.043
Soybean	365.25	784.70	0.195
Generated electricity in Brazil in 2005		402,937	100,000

of energy. The utilization of hydrogen via steam reforming of glycerol associated with fuel cell is an alternative of renewable and decentralized generation of energy with low emission of pollutants.

11. Conclusions

The results allow evaluating the effectivity of hydrogen generation utilizing glycerol via steam reforming. As cited previously, various thermochemical reactions can be developed for this purpose.

A wide range of feedstocks could be utilized to produce glycerol via transesterification of oils and greases. Some calculations were developed to evaluate the potential of hydrogen production and hence, electricity generation via fuel cell. The suggested fuel cells are those operated at high temperatures (such as SOFCs) since high-purity hydrogen is not necessary, diminishing costs with hydrogen purification systems.

In the cited feedstocks the potential of hydrogen production and electricity generation in each Brazilian state were also calculated. For feedstocks such as castor bean, palm, peanut and soybean, the potential of hydrogen production and electricity generation per hectare were calculated, and in the case of residual feedstocks (wastewater scum, defective coffee and beef tallow), the potential of hydrogen production and electricity generation based on volume of available feedstocks were calculated.

The highest potential, as cited above, was encountered utilizing glycerol from palm oil. The potential of electricity generation utilizing this feedstock is 54,600 GWh per annum. The advantage of this feedstock is that its harvest, in contrary to other cultures, is constant, i.e., its harvest can be developed during the year. Taking an assumption of a annual period of operation of 5000 h, the foreseen overall installed power of electricity through fuel cells coupled with steam reforming system is 11.3 GW, an enormous potential which could contribute to increase the quality of electricity supply, inclusively in regions that are not connected with grid. The annual potential of electricity generation utilizing residues is 318.58 GWh with overall installed potential of 63.72 MW. The potential of electricity generation of other feedstocks (castor bean, peanut and soybean) is 1587 GWh/year, with installed potential of 317.49 MW.

Additionally, other feedstocks could be considered; however in Brazil some researches are being performed to increase productivity such as jatropha, sunflower and others. In near future this feedstock will be important to consolidate biodiesel production and hence, glycerol, hydrogen and electricity.

About utilization of biohydrogen for other purposes, this is a good alternative for some industries such as food industries, which utilizes hydrogen especially in hydrogenation process of oils and greases.

In this work, the production of H-BIO was also considered. Utilizing hydrogen produced through steam reforming of glycerol, high amounts of H-BIO and biopropane could be produced.

For process of transesterification, utilizing the cited feedstocks, 56 billion L of ethanol are necessary to develop transesterification process to produce biodiesel and glycerol. Not considering utilization of palm, the amount of ethanol decreases to 2.97 billion L of ethanol. Considering a production of 6000 L/ha of sugarcane, the extension of the areas necessary to produce the calculated volumes of ethanol are 94.148 km^2 (with transesterification of palm oil) and 4.951 km^2 (without transesterification of palm oil). Both values are small compared with available areas to expand this culture.

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